Agricultural and Forest Meteorology 256–257 (2018) 32–45

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Evolution of rain and photoperiod limitations on the soybean growing season in Brazil: The rise (and possible fall) of double-cropping systems

Gabriel M. Abrahão*, Marcos H. Costa

Department of Agricultural Engineering, Federal University of Viçosa, Av. P. H. Rolfs, s/n, Viçosa, MG, 36570-900, Brazil

ARTICLE INFO

Keywords:
Crop calendar
Soybean
Double cropping
Brazil

ABSTRACT

Over the course of a few decades, soybeans in Brazil evolved from being a localized crop, with planting suitable only in regions with long photoperiods, to being the most cultivated crop countrywide. This happened thanks to the development of varieties that allowed changes in the planting calendar, permitting both cultivation in lower latitudes and the adoption of modern double-cropping systems. Here we develop a spatial dataset of Brazilian soy planting-window estimates for rainfed single and double cropping as a function of time during the period 1974–2012 by combining estimates of two important historical limitations: photoperiod and duration and timing of the rainy season. We apply the same methods to future climate estimates to investigate a possible contraction in the area of double cropping due to changes in the rainy season with global change. The resulting dataset agrees with time-invariant official agricultural zoning and optimal yield experiments and provides unprecedented spatial and temporal information on the soy growing season in Brazil. Analysis of the evolution of planting limitations shows that the relaxation of photoperiod limitations gradually made double cropping possible in central–northern Brazil in the 1980s by lengthening the planting window and allowing farmers to make use of a larger portion of the rainy season. Due to these developments, there were 20 Mha potentially suitable for double cropping in 2012, and this potential has been increasingly exploited. Under the constraints of current widely used crop varieties, we predict that climate change poses a severe threat to this potential, causing area reductions of ~17% in central Brazil and 61% in the MATOPIBA region, known as the world's newest agricultural frontier.

1. Introduction

The timing of agricultural management is a determinant factor of agricultural production. Planting dates influence the environmental conditions that crops are subject to, and planting multiple times in a year can drastically change total output (Ray and Foley, 2013). Crop management information is therefore very important for large-scale assessments that depend on crop–climate relationships, such as crop modeling studies (Jones et al., 2016). Although several efforts have been made to compile data on common planting and harvesting dates (Sacks et al., 2010; Portmann et al., 2010), such management practices are known to vary considerably over time due to climatic, socio-economic and technological factors (Kucharik, 2006; Sacks et al., 2010; Ray et al., 2015). Estimating management practices such as planting windows and cropping frequency based on their relationships to climate can be a useful approach (e.g. Stehfest et al., 2007; Waha et al., 2012), but these relationships also change as new technologies present farmers new management options.

A clear example where these relationships have changed over time due to technology is the Brazilian soybean. Brazil produced over 30% of the world's soybeans in 2016, and was the second largest producer (CONAB, 2016; USDA, 2017). The planted area totaled 30 Mha that year, spanning latitudes from 30°S to 2°S. However, until the 1970s most of Brazil's land was deemed unsuitable for soybean cultivation, since early varieties were limited by their sensitivity to short photoperiods.

The soybean (*Glycine max* L. Merr.) flowers earlier when days are shorter. With soybean varieties available before the 1970–80s, flowering occurred much too soon in latitudes below 15°S, where the maximum photoperiod is less than 12.9 h, and the short vegetative period led to short plants and very low yields (Carpentieri-Pípolo et al., 2002, more detailed explanation in Section 2.2.1). This characteristic effectively hindered cultivation of those varieties in low latitudes, and the crop was limited to the southern, extratropical parts of Brazil (Destro, 2001).

During the 1960s, several factors favored an expansion in soybean

* Corresponding author.
E-mail address: gabriel.abrahao@ufv.br (G.M. Abrahão).

https://doi.org/10.1016/j.agrformet.2018.02.031
Received 21 April 2017; Received in revised form 19 February 2018; Accepted 26 February 2018
Available online 20 March 2018
0168-1923/ © 2018 Elsevier B.V. All rights reserved.

cultivation towards central Brazil (latitudes in the range of 10°S–20°S), including rising world soybean prices, low land prices and government incentives for infrastructure (Gavioli, 2013). The acid soils, pest conditions and, most importantly, short photoperiods were challenges to the varieties of that time. But the region also had several attractive conditions, especially a stable rainy season and vast expanses of flat soil suitable for mechanized agriculture (Spehar, 1994; Almeida et al., 1999; Schnepf et al., 2001).

These advantages favored the development of varieties adapted to that region. The first significant research developments in soybean breeding started in the late 1960s at universities and public research institutions, where several photoperiod-tolerant but low-yielding varieties were developed. In the 1970s, the Brazilian government invested heavily in agricultural research. Embrapa (Empresa Brasileira de Pesquisa Agropecuária), currently the largest Brazilian government agricultural research and development agency, was created in 1973, and a branch with the specific goal of developing tropical soybeans started operating in 1975 (Pessôa and Bonelli, 1997). Embrapa and several other research institutions, especially universities, cooperated towards the goal of creating soybean varieties and systems adapted to the conditions of central Brazil while increasing the productivity of the crop (Almeida et al. 1999; Santos et al., 2016).

This effort led, in the beginning of the 1980s, to the release of varieties that were both combine-harvestable and relatively productive under the relatively short days of central Brazil. The possibility of planting in that vast region, where land was cheaper, created a continuous demand for better-adapted varieties (Viana et al., 2013). Later work produced varieties even less sensitive to photoperiod and improved yields under different environmental conditions (Spehar, 1994; Gavioli, 2013). These developments also had the effect of "flexibilizing" planting dates; that is, the new varieties allowed for more flexible planting dates as compared to older varieties. These developments eventually led to irrigated winter soybeans being cultivated in some northern states (Carpentieri-Pípolo et al., 2002). In addition, breeding work that focused on the dependence of crop cycle length on temperature and photoperiod produced varieties with a wide range of cycle length options under different environments (Alliprandini et al., 2009; Cavassim et al., 2013).

These combined factors eventually allowed farmers to plant multiple crops in a single year, leading to the modern prevalence of double-cropping systems (Correa and Schmidt, 2014). Planting a second crop such as maize or cotton after soybeans in the same field, the so-called *safrinha* crop, increases the profitability of land and is associated with higher economic development in Brazil (Arvor et al., 2012; VanWey et al., 2013). These systems are dependent on a rainy season that is long enough to accommodate both crop cycles. To make maximum use of the rainy season, farmers tend to plant the soybeans as early as possible. Although this leads to suboptimal yield from the soybean crop, the profits of the second crop and the higher prices that can be achieved by harvesting earlier can render double cropping an attractive option for farmers (Flaskerud and Johnson, 2000; Borchers et al., 2014).

Soybean planting and harvesting dates are a complex function of time because of the particularities of the relationship between climate and planting dates for double-cropping systems, the great improvements to photoperiod limitations, the interaction between the rainy season timing and the photoperiod, and the interannual variation of the rainy season. This is especially true as double-cropping systems, which were uncommon in the 1990s, became increasingly common over time, such that now 58% of all Brazilian maize is produced as a second crop. Most modeling studies oversimplify this complexity by not considering double-cropping systems and using either a planting date fixed in time and space (e.g. Oliveira et al., 2013), time-invariant maps of global planting dates (e.g. Ray et al., 2015) or date optimization schemes for single-cropping systems (e.g. Rosenzweig et al., 2014).

Here we develop a dataset of estimated planting and harvesting windows for single and double cropping as a function of time during the period 1974–2012. First, we estimate the photoperiod limitations of soybean varieties planted in Brazil in each year based on the spatial distribution of soybean harvested area. Then, combining this information with gridded precipitation data, we derive yearly estimates of the soybean planting window on a $1^\circ \times 1^\circ$ grid for both single- and double-cropping systems. Although available observational data does not allow proper validation that photoperiod and rainy season duration and timing are the most important limiting factors, the resulting dataset compares well with available countrywide planting-date assessments and recommendations. This dataset provides insight into the influence of technological improvements on planting limitations, and the role of those technological improvements in the rise of double-cropping systems. The dataset can also be used as input data for crop models. We also apply the same methods to outputs from Earth System Models (ESMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5, Taylor et al., 2012) to assess the possible impacts of future climate change on soybean double cropping in Brazil.

2. Data and methods

2.1. Gridded soybean area dataset

A Brazil-wide, spatially explicit dataset of soybean harvested area (km^2) in a 1 km × 1 km grid was developed using a methodology similar to the one used by Dias et al. (2016), which used the Global Forest Cover (GFC) dataset for tree cover (Hansen et al., 2013) to perform a spatial disaggregation of Brazilian census data for land use from 1940 to 2012, including harvested areas and yields of soybeans. The version used here has minor modifications with respect to data periods and applies less filtering to ensure pixel by pixel consistency across years for locations where census tracts changed. It covers the study period beginning at the 1974 harvest and ending at the 2012 harvest. Before 1974, census data were not available every year. A more detailed description of the dataset's development can be found in Appendix A.

2.2. Planting limitations

Soybean planting suitability varies with many environmental factors, such as total solar radiation, in-season precipitation, temperatures and complex genotype–environment interactions (Hu and Wiatrak, 2012; Junior et al., 2017), in addition to economic factors such as soybean prices and farmers' propensity to take risks (Boyer et al., 2015). Here we assume that these factors influence the planting decision only inside a broad planting window defined by (i) the rainy season, which is a large-scale limiting factor for planting in Brazil (Waha et al., 2012), especially for double-cropping systems (Spangler et al., 2017); and (ii) photoperiod, which influences plant development and was a strong constraint on expansion of Brazilian soybean agriculture in its earlier years (Spehar, 1994). Frost is only indirectly considered, as the methodology for the photoperiod limitations imposed does not allow planting of the first crop in the winter, and possible effects on the second crop during its final development stages were not considered. All parameters were chosen to be conservative in the sense that they should give the broadest estimates of the planting window at each location. We also considered limitations created by the appropriate phytosanitary legislation enacted in the periods and regions where they were in effect.

2.2.1. Photoperiod limitations

The development cycle of the soybean plant can be divided into two periods: vegetative and reproductive. During the vegetative period, the plant grows in mass and height, allocating the products of photosynthesis to roots, stems and leaves. The first flowers mark the beginning of the reproductive period, when products of photosynthesis are mostly (exclusively, in some varieties) allocated to the reproductive organs. While actual grain filling happens in the reproductive period,

the vegetative period must be long enough for the plant to have a well-developed canopy and root system when the reproductive period begins (Gavioli, 2013).

The duration of the vegetative period depends on complex interactions between the variety's genotype and environmental factors, mainly temperature and photoperiod (Alliprandini et al., 2009). Higher temperatures speed up the development process, while longer days delay it. The sensitivity to photoperiod (in photoperiod-sensitive varieties) is nonlinear, with short days (< 14 h) having a much weaker delaying effect and thus potentially leading to very short vegetative cycles (Cober et al., 2014). Most of Brazil's area is located at latitudes smaller than 30°, where the days are never longer than 14 h. So the first soybean varieties that were brought from the U.S. and Asia had to be heavily modified to be less sensitive to short photoperiods (Destro, 2001; Spehar, 1994).

Continuously developing new varieties that would produce commercial yields despite the short photoperiods of lower latitudes was an essential condition for the expansion; it also had the effect of flexibilizing planting dates (Spehar, 1994; Carpentieri-Pípolo et al., 2002). Cultivars that were suitable for planting only in narrow, long-day time windows in the lowest (northernmost) latitudes cultivated with soy at the time could be planted during wider time windows at higher latitudes. Eventually, the beginning of the rainy season became a stronger limiting factor for planting than daytime length in most regions with prominent precipitation seasonality (Waha et al., 2012).

During the study period, common soy varieties reached full maturity in about 110–140 days (Alliprandini et al., 2009; Cavassim et al., 2013). Varieties with significantly shorter cycles are continuously being developed and were explored as an alternative scenario for the future (see Section 2.5). The soy plant fills grains until late in the reproductive period, at about 100–130 days after planting (Alliprandini et al., 2009; Bezerra et al., 2016). By comparison, the most common second crop, maize, has a typical cycle length of 120–140 days. Keeping plants from water stress until grain filling is complete is important to maximize yields, but it also creates a planting-window limitation at the end of the rainy season, as planting too late in the rainy season may lead to water stress at the end of the cycle. This limitation is especially important for the now common double-cropping systems, where planting must occur as soon as possible to accommodate two cycles. We present a methodology to estimate the evolution of these planting windows.

Here it is assumed that a significant number of farmers in a latitude band would have planted the soybean crop only after, and as soon as, they had access to varieties well-adapted to their longest photoperiod dates (i.e. around the austral summer solstice, about December 21). Using the yearly 1 × 1 km soybean planted area maps, the northernmost pixel that had at least 1% of its area planted with soybeans was considered for calculating the minimum photoperiod needed for commercial varieties in each specific year. The 1% threshold was chosen because smaller fractions do not represent areas with well-established soybean farming and thus were removed from the analysis. The results are qualitatively very similar if a threshold of 0.5% is used instead.

Here we assumed a vegetative period of 45 days. This is considered by Gavioli (2013) as the minimum for optimum yields, and it is among the smallest values found by Alliprandini et al. (2009). With the methods described below, the sensitivity of the results to changes in this value is a maximum of half a day for each day of change. For example, if the vegetative period were assumed to be 39 instead of 45 days, the earliest photoperiod-limited planting dates would be 3 days earlier than our estimates, and the latest photoperiod-limited planting date would be 3 days later. To give the crop the longest possible days in this period, the planting date should be half this time (i.e. ~23 days) before the austral summer solstice, at around November 30, putting the solstice (December 21, the longest day) in the middle of the 45-day period and thus maximizing the average photoperiod during the vegetative period. For a given year, this is the single planting date possible for the lowest (i.e. closest to 0°) latitude where a variety could be planted. This also means that, as the soybean frontier moved northward, the northernmost farms were always planted around November 30 in order to achieve optimal yields.

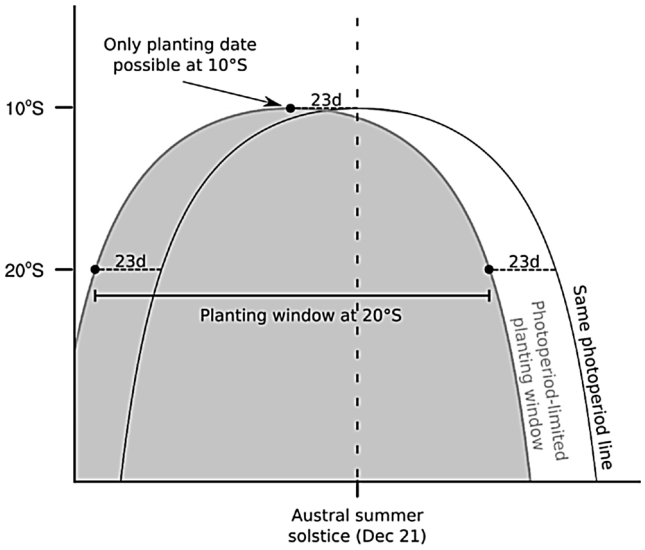

Fig. 1. Chart illustrating the methodology used to define the photoperiod-limited planting window for a given year. In this example, the northernmost latitude where soybeans were harvested is 10°S.

In every latitude south of that reference, we determined the two dates for which the photoperiod is the same as the summer solstice photoperiod of the reference latitude: one date after, and one before the solstice. The photoperiod-limited planting window was then delimited as a function of N, where N is the summer solstice photoperiod applicable to the lowest latitude that had soybeans for each year of the study. For each latitude, the planting window is the period between (Fig. 1):

(i) 23 days before the day with photoperiod N, before the summer solstice; and
(ii) 23 days before the day with photoperiod N, after the summer solstice.

The astronomical equations used to derive these dates are straightforward and are presented in Appendix B.

2.2.2. Rainy season limitations

For rainfed systems, the planting window also depends on the rainy season, so an analysis of its onset, end and duration was also performed. Only a few available datasets provide precipitation data at the country scale for the period of analysis (1974–2012). Even data derived primarily from observations is subject to uncertainties related to the interpolation method and station selection, particularly in Brazil where the station network increased considerably during the period of analysis (Xavier et al., 2016). The data used here is gridded (1.0° × 1.0°) daily precipitation from the Princeton University Terrestrial Hydrology Research Group (PTHRG, Sheffield et al., 2006), which is a merge of several datasets, including the Tropical Rainfall Monitoring Mission (TRMM), Global Precipitation Climatology Project (GPCP), the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis and the Climate Research Unit (CRU) station-based dataset, and covers the 1974–2012 period.

To determine the onset and end of the agricultural rainy season, we used a modified version of the Anomalous Accumulation method (AA, Liebmann et al., 2007), which was successfully used by Arvor et al. (2014) for the same purpose for the Brazilian state of Mato Grosso using gridded data from the TRMM 3B42 product. The advantage of this method is that it defines the rainy season as a period of precipitation

consistently above a reference that can be set to an agronomically meaningful value. The Anomalous Accumulation (AA, mm day^{-1}) of day t is calculated as

$$AA(t) = \sum_{n=1}^{t} (R(n) - R_{ref}) \quad (1)$$

where R(n) is rainfall for day n and R_{ref} is a reference rainfall value, both in mm day^{-1}. The onset and end dates of the rainy season for each year are defined as the days of minimum and maximum (respectively) AA for that year. Here, t starts on July 1, in the middle of the dry season in most of Brazil, and ends on June 30 of the following year. The value of R_{ref} used was 2.5 mm day^{-1}, representative of a soybean seedling's needs.

2.2.3. Phytosanitary legislation

Since 2007, several Brazilian states have adopted regulations that prohibit the existence of living soybean plants in the field during a certain period, called *vazio sanitário*, or sanitary break (MAPA, 2007). The objective is to control the Asian soybean rust (*Phakospora sp.*), and the period usually lasts around two months. Each state adopted this practice at a different time, and the specific dates changed in some states during our period of study. The dates used here can be found in Supplementary Table S1.

2.3. Planting and harvest calendars

Based on these limitations, two planting calendars were developed for soybeans both as a single crop and as the first crop in a double cropping system at each year were developed. The first is a photoperiod and meteorological rain calendar (PMR), based on the rainy season and photoperiod limitations of each year. It represents the estimated limitations experienced for each year and includes the effects of inter-annual variability.

The other, a photoperiod and climatological rain calendar (PCR), also incorporates changes to photoperiod limitations over time, but it uses a limitation based on a fixed climatological rainy season. It is used to characterize the long-term temporal evolution of possible planting windows caused by the relaxation of photoperiod limitations at each latitude. It also represents a risk-based view of the rainy season, taking into consideration the 20% of years with the latest rainy season onset dates (80th percentile), and it can be compared to currently available data for climatologically determined soybean cropping periods.

For the photoperiod and meteorological rain calendar (PMR), the following criteria were applied:

- The earliest possible planting date is defined as either the earliest day of the photoperiod-limited planting window calculated using the latitude closest to the equator of each year or the rainy season onset of each year, whichever happened later.
- The latest possible planting date is defined as the earliest date between: (i) the latest photoperiod-limited planting date and (ii) 90 days before the rainy season end for single-crop soybeans or 200 days (110 for soy plus 90 for a second crop) before the rainy season end for double-crop systems. This is a conservative approach, as it considers a relatively short 110-day soybean cycle and a second crop with the same cycle length, while the commonly planted maize and cotton have longer cycles. The usage of 90 days before the rainy season end also assumes a 110-day cycle but considers 20 days of use of soil moisture at the end of the cycle.
- The latest possible harvest date is defined as 30 days after the rainy season end. This assumes soil moisture usage for 20 days and 10 days for drying the grains before harvest.

As discussed earlier, the total cycle of 110 days for both crops was chosen as a low value representative of soy varieties of the late 2000s. The same value was applied to the second crop, despite maize generally having a longer cycle, to produce conservative estimates. The value of 20 days of soil moisture usage was chosen considering full usage of 16% of available soil moisture, 30 cm effective root depth and 2.5 mm day^{-1} evapotranspiration. These parameters may vary with factors such as soil type, management practices and plant drought tolerance, and the values used are conservative for common soils, varieties and management practices in Brazil (e.g. Moreira et al., 2015). We choose to describe most of the parameter values as durations (e.g. time to flowering, cycle duration, time for soil moisture usage, time for grain drying) to make their effects on results as transparent as possible.

The criteria for the photoperiod and climatological rain calendar (PCR) are the same as in the meteorological rain calendar, except that the rainy season onset date used for all years was set to match the 20% latest onset dates (80th percentile) for the 1974–2012 period, representing a one in five risk of seedling failure. This level of risk is the same as that adopted in the Brazilian Agricultural Zoning (Bambini et al., 2015). The climatological rainy season end was defined as the date of rainy season onset for the latest 20% of the years in the analysis (the 80th percentile) plus the median rainy season duration for the same period.

In this methodology, we assumed fixed values for a few parameters, such as total cycle length, duration of the vegetative period and time of use of soil moisture. The methods can easily be replicated using different values for these parameters by adding or subtracting the change in them to the earliest or latest dates accordingly.

2.4. Comparison with existing datasets

To our knowledge there are no other soybean cropping calendars with yearly information currently available. Thus, we compare the climatological calendar of the year 2012 (PCR2012) with four other time-invariant datasets to check the reasonableness of the results. The datasets used represent different definitions of the growing season that are specific to their applications.

The global dataset from Sacks et al. (2010) provides common planting and harvesting periods for 19 crops in a 5′ grid. The underlying data, however, are subnational statistics that divide Brazil into a few large regions. It is generally used as input for crop models (e.g. Rosenzweig et al., 2014). The MIRCA2000 (Portmann et al., 2010) dataset is similar in sources and uses to Sacks et al. (2010) in regard to soybeans, but it has coarser intra-annual information as it only reports the typical start and end month of the growing season instead of the planting and harvest periods.

Silva et al. (2015) reviews the Brazilian literature on field experiments that aim to find optimal yield planting dates for each site. The compilation is aggregated by major regions and provides information on the narrow periods that maximize yields of single-crop soybeans, not accounting for other factors such as double cropping or availability of agricultural credit.

Agritempo (http://www.agritempo.gov.br; Bambini et al., 2015) is a governmental platform that provides information on very low-risk planting windows for various crops. It is based on climatological restrictions, and planting within these dates is required by some financial institutions for securing agricultural credit (i.e. credit is released only when the planting window starts). Fraction of soy planted using credit (although not all credit is necessarily restricted by these criteria) varies largely from state to state, from 24% in Mato Grosso to 80% in Paraná (2010 data) (Anuário Estatístico do Crédito Rural, www.bcb.gov.br).

2.5. Future climate change

To demonstrate the applicability of the method to other climate inputs and provide estimates of future soybean planting windows, we also calculate them for the CMIP5 RCP8.5 climate change scenario for the next few decades (2010–2050, Riahi et al., 2011). It is a scenario of

comparatively high greenhouse gas emissions, but it is also the one that best represents the emissions measured since its development (Fuss et al., 2014). In addition, before 2050, climate change does not differ much among the scenarios, so the use of one scenario is sufficient. Photoperiod limitations were fixed at the most recent (2012) values, effectively a minimum of 12 h, and rainy season estimates were calculated for the CMIP5 ESMs' outputs.

For this analysis, the ESMs used were first screened for suitability. The method used to define the rainy season requires daily precipitation data, and the results are very sensitive to the distribution of rainfall throughout the year, which most of the CMIP5 models do not simulate well over Brazil (Pires et al., 2016). Therefore, instead of using many models to account for model-specific biases, we chose the ones that best simulate the rainy season onset and end over the region of study when compared with the PTHRG dataset for the period 1973–2005.

Starting with the four models selected by Pires et al. (2016, namely HadGEM2-ES, MIROC5, CCSM4 and MRI-CGCM3, Supplementary Table S2), we apply the AA methodology and compare the frequency of rainy season durations with that of the PTHRG dataset (Supplementary Fig. S1). The HadGEM2-ES model clearly stands out among the other models, showing the frequency pattern closest to that of the reference data. Except for southern Brazil, the difference is less than 10 days for most frequencies in all regions. Due to this outstanding performance, we chose to use only the HadGEM2-ES output to evaluate future planting windows. Although the results may be contaminated by possible model-specific biases, Supplementary Fig. S1 shows that using an ensemble of the available models would clearly bias the results towards shorter rainy season durations and consequently shorter planting windows.

Since the end of our study period, breeders have developed soy and maize varieties with cycles even shorter than the 110 days used here for historical varieties. Soybean varieties such as Embrapa's BRS 6980 (released in 2017) have been reported to reach maturity within around 100 days in central Brazil, and lower-yielding maize varieties for semi-arid regions such as BRS Gorutuba (released in 2010) show similar cycle durations. To account for the possibility of shorter-cycle varieties in the future, we estimate future double-cropping soybean planting windows considering cycles of 90 and 110 days for both soybeans and the second crop. We also do not consider the phytosanitary regulations of the sanitary break period in our estimates for the future, assuming that regulatory agencies may shift the period earlier or later in the year should it become a severe limiting factor.

3. Results and discussion

3.1. Spatial patterns of the soybean expansion

Total soybean harvested area grew from 5.1 Mha to 24.9 Mha in the period 1974–2012. The geographical extent of this expansion was wide, as the number of states with appreciable soybean presence (defined as 1% of each 1 km^2 pixel) doubled in the study period (from 7 in 1974 to 14 in 2012, Fig. 2). The expansion started from southern Brazil (Figs. 2 and 3). In 1974, 83% of the soybean area was located south of the Tropic of Capricorn. Despite the growth in area (to 8.2 Mha in 1979), the expansion was constrained to southern Brazil and parts of SP (São Paulo), MG (Minas Gerais), MS (Mato Grosso do Sul) and southern GO (Goiás) until the 1980s. By then, researchers were able to introduce in commercial varieties a trait that delayed flowering despite the photoperiod (Spehar, 1994; Carpentieri-Pípolo et al., 2002). As a consequence, soybeans rapidly started to spread to MT (Mato Grosso) and northern GO, eventually reaching western BA (Bahia). Most of these new regions are in the *Cerrado* biome, while some of northern MT is in the *Amazonia* biome.

By 1989, nearly half (6.2 Mha out of 12.2 Mha) of the soybean area was in the intertropical region. During the 1990s, the expansion was relatively slow, as harvested area rose by only 0.85 Mha from 1989 (12.2 Mha) to 1999 (13.0 Mha), a fact that may have been due to a convergence of economic factors that favored intensification over extensification (Melo, 1999). However, soybean area grew considerably in the *Cerrado* biome, which had 4.4 Mha of soy harvested in 1989 and 6.0 Mha in 1999. During the 2000s, the expansion again gained momentum as the harvested area nearly doubled from 1999 (13.0 Mha) to 2012 (24.9 Mha). About half (6.3 Mha) of this increase happened in the *Cerrado*, which represented half of total soybean area in 2012 (12.3 Mha). Soy presence in the states of MA (Maranhão), TO (Tocantins), PI (Piauí) and BA, in the northeastern *Cerrado*, expanded greatly in the 2000s. This region, known as MATOPIBA, has been described as the world's newest agricultural frontier. Total soybean harvested area in MATOPIBA tripled from 1999 (0.8 Mha) to 2012 (2.5 Mha). In 2012, 65% of the soy area (16.3 Mha) and 74% of the soy production (48.9 Mt) were to the north of the Tropic of Capricorn. This expansion is depicted in Fig. 4a,b. Fig. 4a shows the changing soybean extent over time using different color codes for different periods, while Fig. 4b shows the lowest (northernmost) latitude where soybeans were present each year.

3.2. Evolution of planting limitations

On zonal average, the photoperiod was the limiting factor for the soybean planting window at all latitudes until the beginning of the 1980s (~1984, Fig. 4c), when the rainy season onset became the limiting factor for latitudes between 24°S and 16°S. The start of the planting window became limited by the rainy season in most regions during the 1980s (Fig. 5). The most notable exception is southern Brazil, where rain is well distributed throughout the year. As of 1990, planting windows in all latitude bands north of 25°S, where the rainy season is well defined, were on average already limited by the rainy season, or the photoperiod limitation was very close to the defined rainy season limitation (corresponding to a one in five risk of planting before the start of the rainy season, Fig. 4c). Exceptions are the northernmost portions of MT and MATOPIBA, which were limited by photoperiod until the late 1990s (Fig. 5).

This is consistent with reports of the "first cycle" of soybean breeding in Brazil, which had the main objective of obtaining late-flowering varieties suitable for the low latitudes of the *Cerrado* and lasted until the late 1980s (Spehar, 1994). However, despite the photoperiod no longer being a limiting factor for planting, it still has a strong influence on yields, and is one of the determinants of optimal-yield planting dates (Alliprandini et al., 2009; Silva et al., 2015). The sanitary break was the limiting factor for some regions after its introduction in 2007 (Fig. 5), but even in these regions its influence is less than 10 days in PCR (not shown). This is expected, as the sanitary break is normally designed so as to not interfere with common planting practices and usually ends before the rainy season begins.

Progressively overcoming photoperiod limitations through plant breeding has also had the effect of flexibilizing possible planting dates. For example, the 18°S latitude band (see black line in Fig. 4c) had a climatological 46-day planting window in 1974, and by 1989 farmers at that latitude could exploit their full rainy season, leading to a climatologically low-risk 116-day planting window. This effect is progressive and more prominent in regions that have been exploited in this way more recently, due to the "flat-top" shape of the arcsine curve that describes the photoperiod limitations. It has also been fundamental to the northward expansion of rainfed double-cropping systems.

Double-cropping systems started being used in the state of Mato Grosso only in the 1990s, first as a way to reduce economic and environmental vulnerability to pests by planting a cheaper second crop; over time, practices evolved toward modern soy–maize and soy–cotton systems, where the second crop can be as economically important as the first (Arvor et al., 2012). Early experimentation with soy–soy systems demonstrated that planting soy crops in immediate succession results in an unsustainable phytosanitary risk (Garcia et al., 2015).

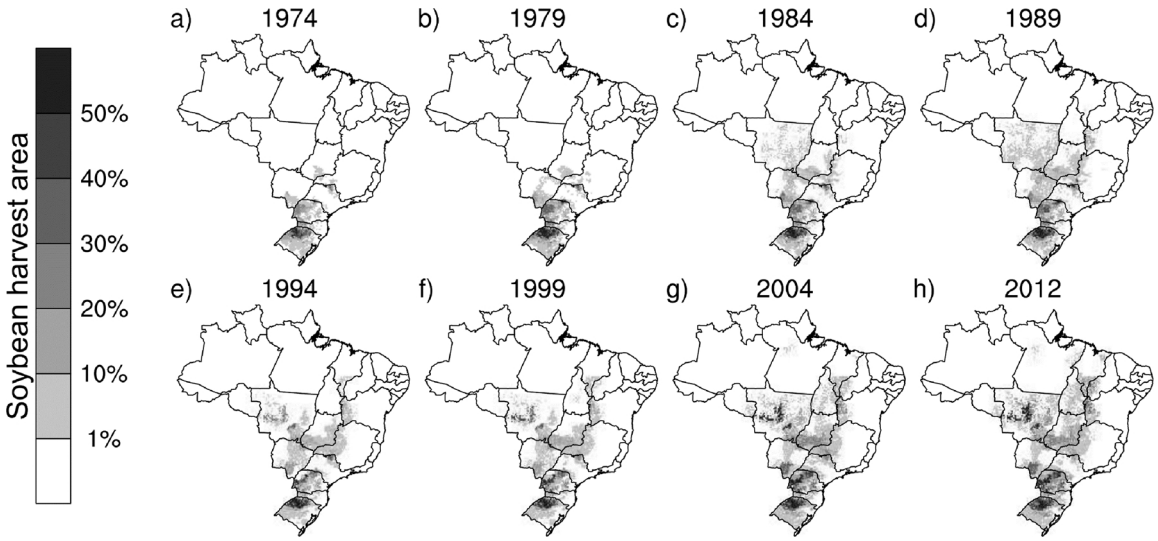

Fig. 2. Expansion of soybean harvest area in selected years.

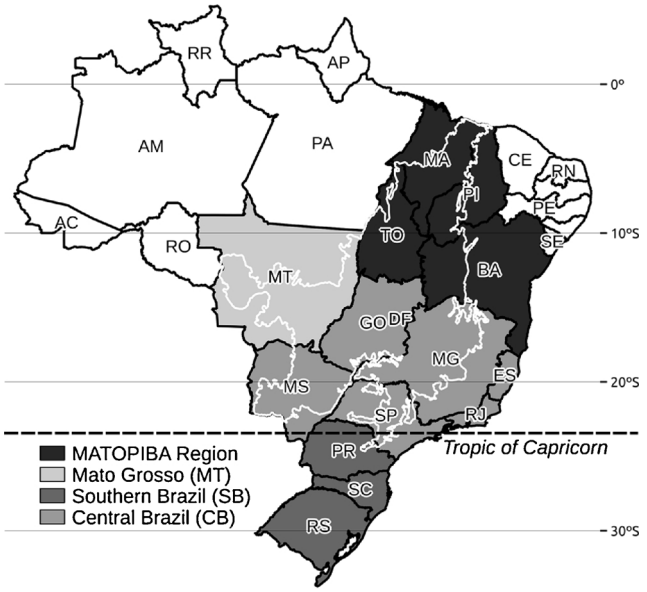

Fig. 3. Brazilian states and regions of analysis. The solid white line delineates the *Cerrado* biome.

Results indicate a strong flexibilization of planting dates for double-cropping systems (Figs. 4d and 6). Latitudes of northern MT, for example, (10–14°S) had the potential for supporting double-cropping systems in 1984, but only in a very narrow planting window. After 1990, however, planting was possible right after the rainy season started in the late-onset years. The yearly evolution of these limitations (Supplementary Fig. S2) shows that double cropping in southern MT was made possible in progressively larger areas by the gradual overcoming of photoperiodic limitations between 1980 and 1984. These results indicate that not only the expansion of soybeans to MT but also the feasibility of planting two crops were results of the development of photoperiod-insensitive varieties in the first cycle of soybean breeding in Brazil.

Although this is, to our knowledge, the first work to quantify the large-scale effects of overcoming the photoperiod barriers, the flexibilization of planting dates is known to have been an effect desired by breeders (Spehar, 1994). Given that our methodology uses the northernmost latitude with harvested soybeans as an indicator of the photoperiod dependence of varieties available in each year, our results may detect the introduction of new technologies late, as they will only be detected when adopted at the frontier latitudes. However, during the rapid expansion of the 1970s–80s, technology adoption by pioneers was known to be very fast. Varieties suitable for planting northward of 15°S are reported to have been developed in 1980 and made available to the general public about two years later (Spehar, 1994; Destro, 2001), near the time when our methods first detect harvest northward of 15°S (Fig. 4b). Moreover, the facts that (1) experimental optimalyield planting dates are generally close to the beginning of the rainy season (Silva et al., 2015, see next section) and (2) double-cropping systems depend on planting as early as possible are strong indications that, in addition to allowing the northern expansion of tropical soybeans, the radical changes in photoperiod dependence during 1974–1990 had a strong influence on the efficiency and profitability of soybean farms through the flexibilization of planting dates.

This effect is also verified when accounting for the interannual variability of climate using the PMR calendar (Fig. 7). During the period of study, more than 90% of MT and a large portion of CB (central Brazil) soybean area crossed the assumed double-cropping possibility threshold of 200 days of growing season. Although double cropping was possible in almost all the soy area of 1974, when the crop was constrained to SB (southern Brazil) where rains are well distributed throughout the year (Fig. 6i), planting date flexibilization was essential to allow double cropping in the later-exploited regions. The regions where Fig. 6 shows the possibility of double cropping contain almost all double-cropping areas mapped in central and northeastern Brazil by both Spera et al. (2016) and Spangler et al. (2017), except for some regions in northeastern Brazil where irrigation is common (ANA, 2017). With the combined effects of flexibilization of planting dates and expansion to new areas, double cropping was possible on 20 Mha of the 24 Mha from which soybeans were harvested in 2012 (Fig. 7b).

However, not all of this area is actually used for double cropping. Although there are no national data on systems with specific crop pairs, second-crop (*safrinha*) maize is mostly grown after soybeans, and this combination is also the most common kind of double cropping in Brazil. Other combinations such as soy–cotton or soy–soy are also used, although they are much less common. In the 2012 harvest, only 7.6 Mha of second-crop maize were harvested (CONAB, 2012), from about 37% of the area where double cropping is possible, taking into account the rain and photoperiod limitations. There are other limitations on the adoption of those systems, such as spatial variation of precipitation inside the ~110 × 110 km pixels used; intraseasonal climate variations such as dry spells and frost events; and several economic factors such as credit availability and commodity prices. Our definition of double-

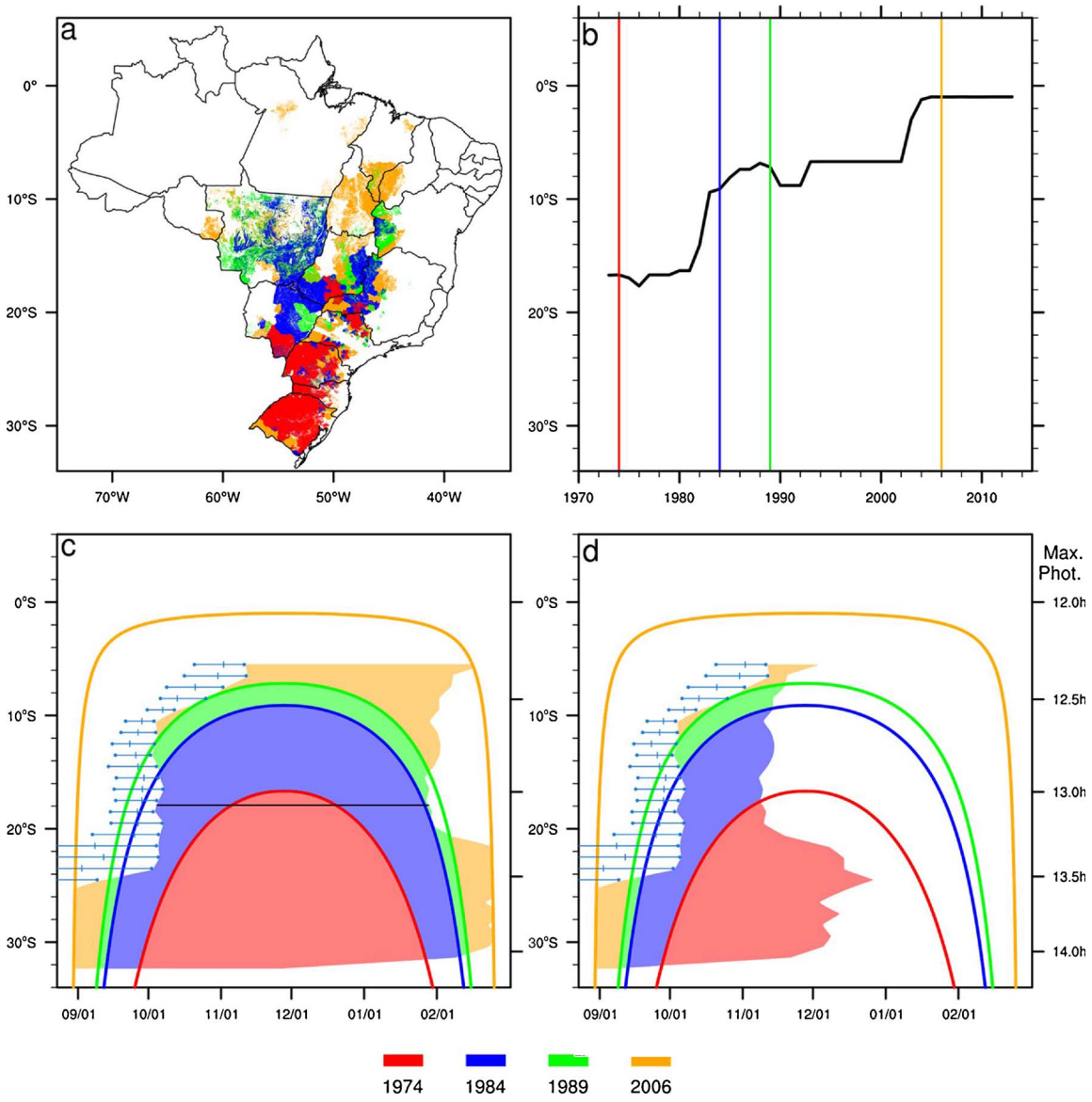

Fig. 4. (a) Location of soybean areas for various harvest years. The color of each 1 × 1 km pixel represents the earliest year when soybeans were harvested from at least 1% of its area; (b) Lowest (northernmost) latitude with harvested soybeans for each year, selecting harvest years when the lowest latitude plateaued; (c) Estimation of the zonal average planting window for selected harvest years (PCR). Solid, thick lines represent the planting date windows considering only the photoperiod limitations of the varieties available during the selected harvest years. Light-blue horizontal bars represent the earliest rainy season onset date for 80% (left dot), 50% (vertical bar) and 20% (right dot) of the years considered, weighted by soybean harvested area in each 1° band of latitude. The shaded areas represent the possible planting window for a single crop of soybeans, assuming a 110-day cycle, taking into consideration the limitations of photoperiod and the onset and end of the rainy season; (d) Same as (c), but shaded areas represent the planting windows for soybeans in a double-cropping system with a combined cycle of 220 days (110 for soybeans + 110 for maize). The right vertical axis shows the maximum photoperiod at each latitude. The black horizontal line in (c) refers to the 18°S example in the text. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cropping possibility does not consider the profitability of the system, which can also depend on other climatic factors that drive the yields of both soybeans and the second crop, such as solar radiation, temperature and intraseasonal rainfall distribution (Hu and Wiatrak, 2012). The likelihood of soybean land being used for double cropping in MT, for example, was found to depend largely on minimum and maximum temperature, slope, access to transportation networks and existing ties to large commodity markets (VanWey et al., 2013; Spera et al., 2014).

Even considering these factors, double cropping may actually be feasible in a large part of the estimated ~60% of soybean area where double cropping was possible but not practiced in 2012. Spera et al. (2014) estimates that ~50% of all the area in MT that was not used for double cropping soybeans in 2011 had characteristics very similar (within 0.5 standard deviation) to the areas that used double cropping in 2001. In fact, the harvested area of maize as a second crop has increased by about 40% in the last four years, from 7.6 Mha in 2012 to 10.5 Mha in 2016 (CONAB, 2016). This indicates that the transition from single- to double-cropping systems is ongoing, and the latter may quite soon become the norm in areas where it is possible. Exploiting the large area that has potential for double cropping could be a sustainable path to increase agricultural production without further land conversion.

Climate change, however, could significantly reduce that potential (Fig. 7). The HadGEM2-ES results indicate that if soybean locations and varieties do not change, shorter rainy seasons may cause a reduction in area suitable for double cropping of 10% from 2013–2030 to 2031–2050. Although southern Brazil presents a slight increase (0.2%), the reduction signal is present in central Brazil (17%), MT (18%) and especially in MATOPIBA (61%). The use of currently hypothetical 90-day varieties for both crops leads to smaller reductions: 7% in CB, 4% in

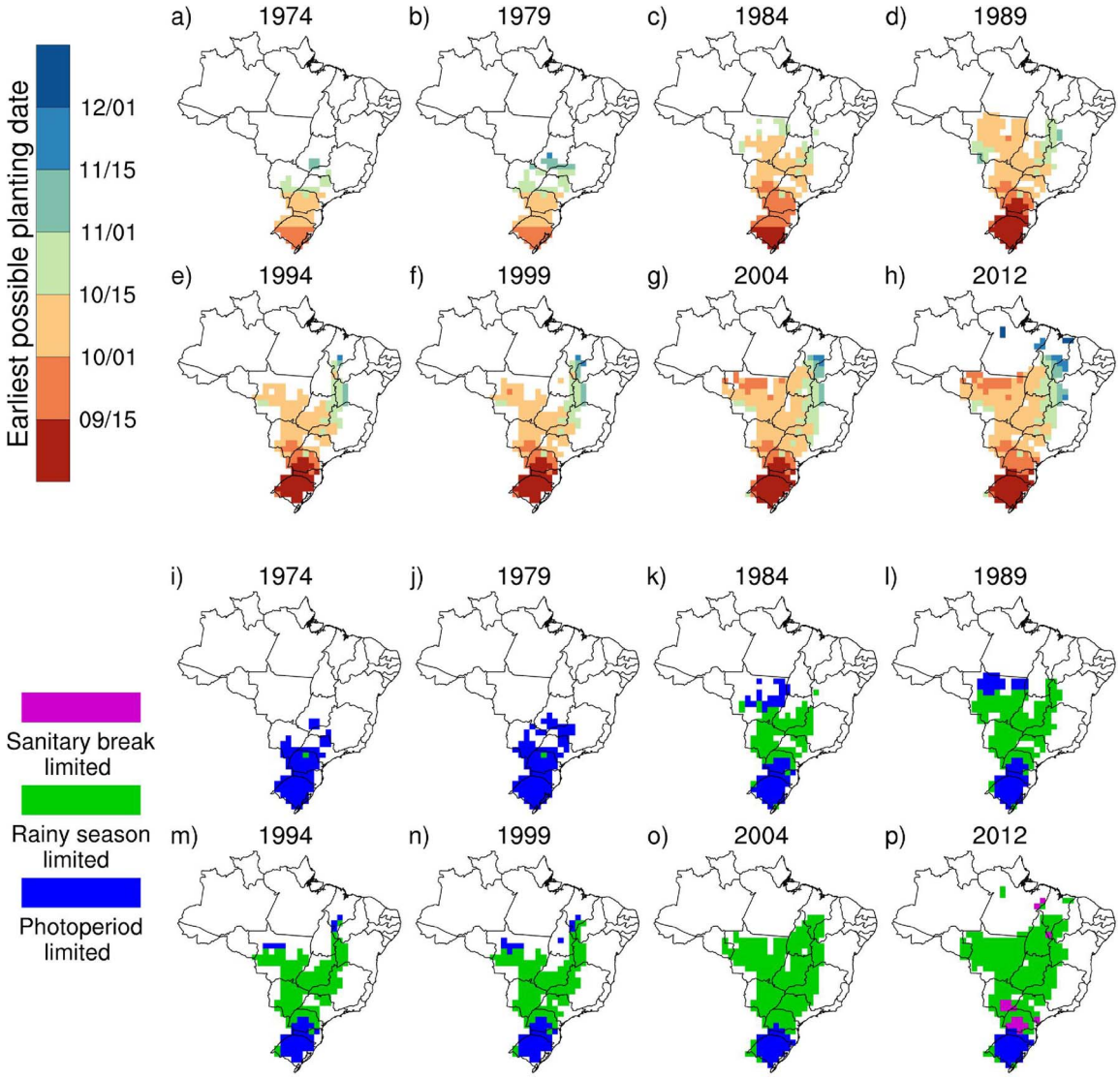

Fig. 5. Estimated earliest single-cropping planting dates for selected years for the photoperiod and climatological rain calendar (PCR, a–h) and the corresponding limiting factors for those planting dates (i–p).

MT and a still very strong 29% in MATOPIBA. In these three regions, the average area where double cropping is possible not only decreases, but also becomes very irregular from year to year (Fig. 7b). The use of 90-day varieties strongly dampens this variation only in MT. Although this pattern could be an ESM-specific trait, arising from the choice of a single climate model for the predictions, HadGEM2-ES simulates the interannual variability of the rainy season reasonably well for the 1973–2005 period (Supplementary Fig. S1). This irregular behavior, if realized, suggests increased climate risk and may push farmers to abandon the double-cropping practice. A strong decline in the climatic aptitude for double cropping in MATOPIBA by the mid-twenty-first century was also found in another study using crop modeling (Pires et al., 2016) and is of particular importance due to MATOPIBA's current status as the world's newest agricultural frontier (Miranda et al., 2014; Spera et al., 2016).

One can argue that the described reductions in double-cropping suitability do not necessarily imply reductions in practice, as double cropping is not practiced in all of the area where our analysis indicates it is possible. However, although available data on second crops is limited, all data indicate approaching saturation of the double-cropping potential in these regions. First, as discussed above, remote sensing studies indicate it is practiced in most of the spatial extent of that area (Spera et al., 2016; Spangler et al., 2017). Second, census data for second-crop planted area is only available for maize, which is the most common, but definitely not the only, second-crop choice (Fig. 7b). Although it is an underestimate of total double-cropped area, it is useful to note that second-crop maize planted area has more than doubled in Brazil since the beginning of census data collection (2003), with more notable increases seen in CB and MT. For the latest period with double-crop potential calculated with actual climate data (2008–2012), the second-crop maize harvest area in 2016 was 86% and 108%, respectively, of our average possibility estimates for CB and MT, indicating a relative saturation of the estimated potential. For the initial period of simulated climate data (2012–2016), the second-crop area data cannot be properly compared with our potential area estimates because, as discussed before, climate models are not designed to match exact years, but long-term climate means and variability. In addition, irrigated second-crop maize is also counted in the census data and is common in some regions, especially in MATOPIBA (ANA, 2017). Moreover, MATOPIBA sustained severe crop failures in the 2016 harvest due to anomalous climate conditions, but yielded 71% of the harvest possibility estimates for 2015. Although, due to data limitations, these comparisons are far from adequate, they illustrate the approaching saturation of the double-cropping potential in these regions.

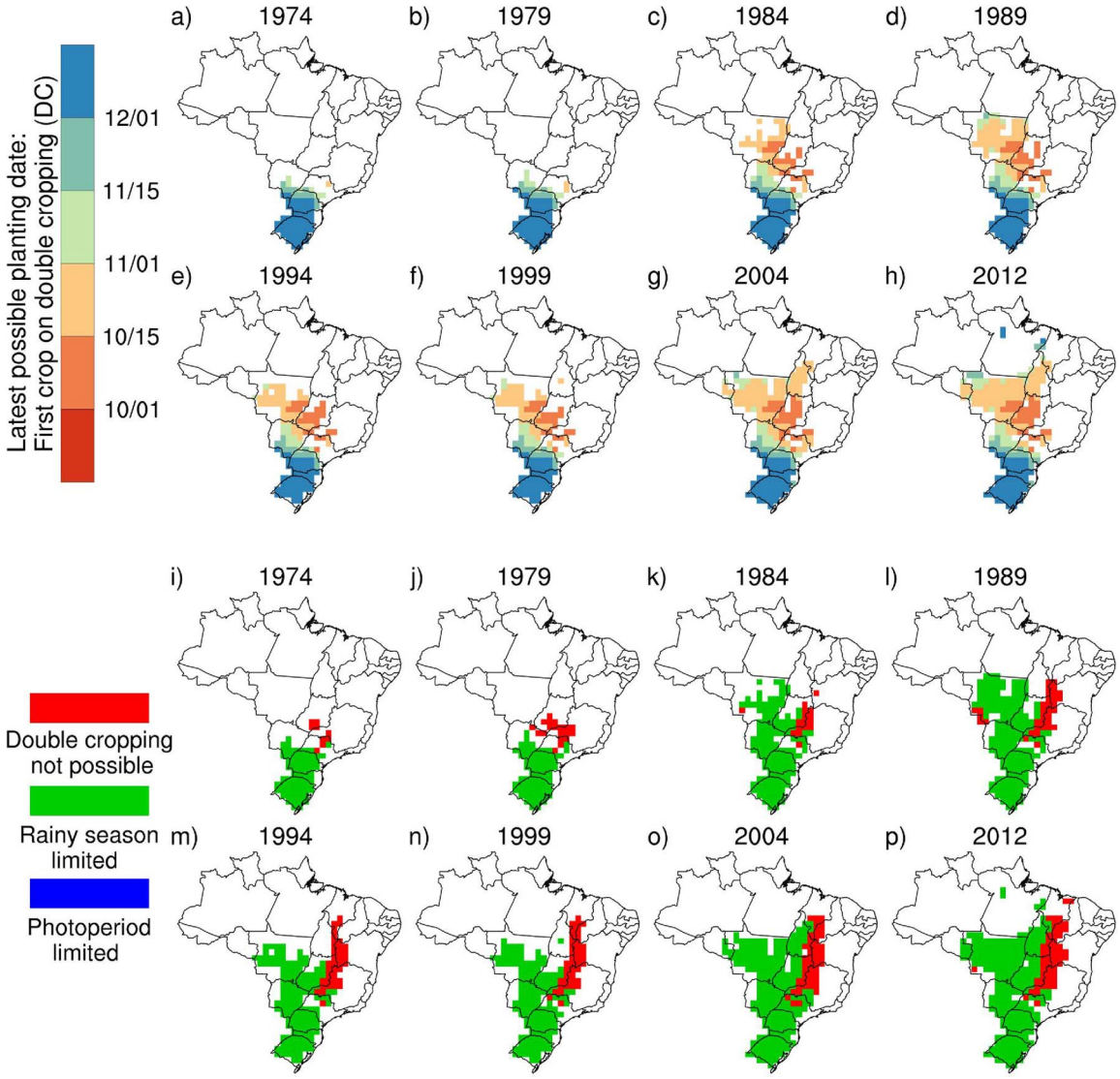

Fig. 6. Estimated latest planting dates of the first crop in a double-cropping system for selected years for the photoperiod and climatological rain calendar (PCR, a–h) and corresponding limiting factors for those planting dates (i–p). Pixels are labeled "not possible" if the earliest possible planting date calculated (based on the rainy season onset) is after the latest possible date calculated (based on the rainy season end). This occurs when the rainy season in 20% of the years is too short or if the photoperiod limitations make the usable part of the rainy season too short for exclusively rainfed double cropping.

This vulnerability of double-cropping systems to future shortening of the rainy season may lead to a destructive feedback loop that could further reduce double-cropping area. First, there is evidence that future shortening of the rainy season in *Amazonia* and the *Cerrado* is exacerbated by the removal of natural land cover, an effect caused by several factors, such as the smaller land–atmosphere water-recycling potential, higher albedo and lower surface roughness of croplands (Dirmeyer and Shukla, 1994; Costa and Pires, 2010; Pires et al., 2016; Wright et al., 2017; Khanna et al., 2017). Second, the adoption of double-cropping systems can potentially slow deforestation, as it may spare land that would otherwise be used to produce the second crop (Barretto et al., 2013). Finally, double-cropping systems were recently shown to have much higher water-recycling potential than single cropping systems, being more similar to the natural vegetation of the *Cerrado* over a longer portion of the year (Spera et al., 2016). The combination of these three factors could lead to a feedback where the reduction of double cropping due to global climate change leads to more deforestation and thus a stronger shortening of the rainy season, enhancing the negative effects by further reducing the area where double cropping is possible. These interactions could be moderated by changes in public and private land-use policies, such as the forest code (Soares-Filho et al., 2014) and the soy moratorium (Kastens et al., 2017). Although this effect must be better understood, it reinforces the notion that the widespread adoption of double-cropping systems can be a way of minimizing human impacts on the hydrological cycle (Spera et al., 2016).

Naturally, the rainy season analyses presented here are subject to uncertainties, presumably large ones, present in both the past precipitation dataset (PTHRG) and the climate model used (HadGEM2-ES). However, it should be noted that the rainy season durations calculated from HadGEM2-ES historical-period output are very close in mean and distribution to those calculated from PTHRG for the same period (Supplementary Fig. S1). Therefore, it can be expected that errors associated with each may be of similar sign and magnitude and that the actual errors in the differences between historical and possible future double-cropping areas are smaller than the errors in the two precipitation series.

3.3. Comparison with existing datasets

All recommended planting dates found in Silva et al. (2015) fall inside the possible planting windows (Table 1). With the exception of

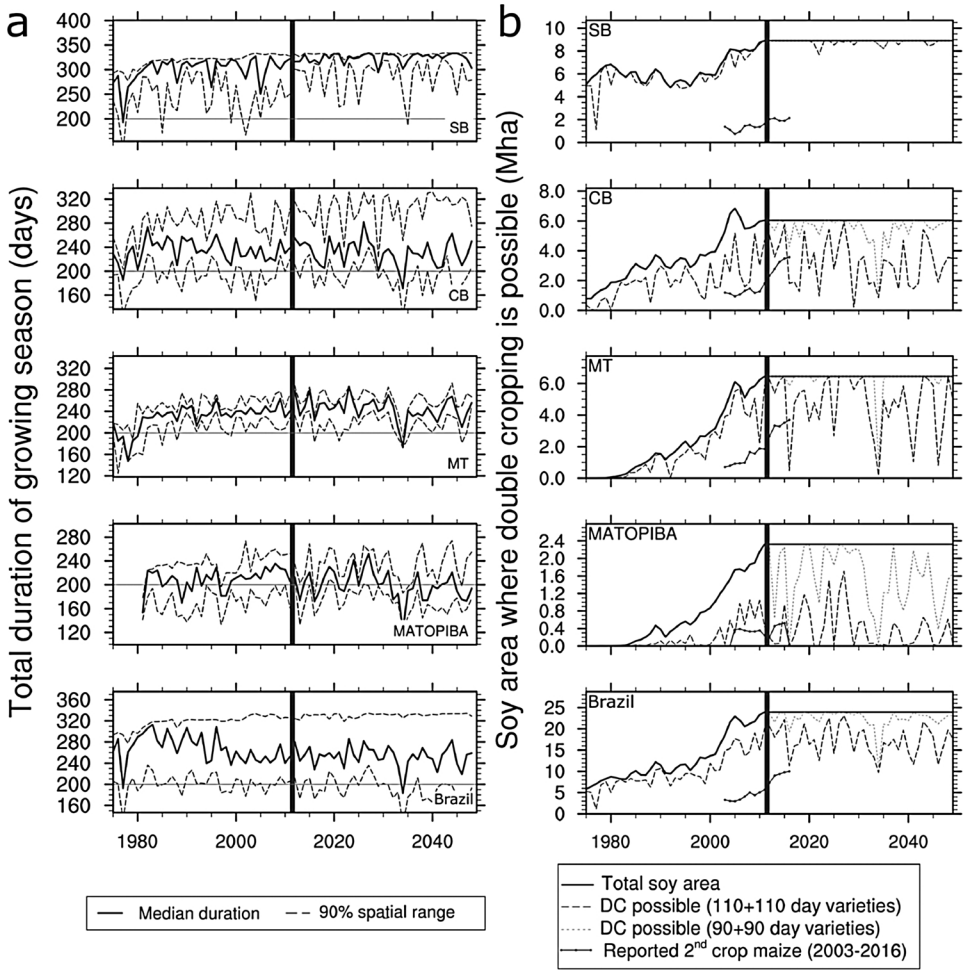

Fig. 7. Changes in growing season duration (a) and soybean area where double cropping is possible (b). Thick vertical bars separate the historical period (1974–2012), analyzed using the PTHRG dataset, and the future period, estimated using the HadGEM2-ES model's CMIP5 RCP8.5 output. The differences between the 90% spatial range lines in (a) represent 90% of all pixels in each region around the median. Solid lines with dots in (b) show census data for second-crop maize harvested area. DC: Double cropping; SB: Southern Brazil; CB: Central Brazil; MT: Mato Grosso state. For region definitions see Fig. 3.

southern Brazil, where the high latitudes and poorly defined rainy season make the planting window very wide, the recommended planting dates are within the first 90 days after the earliest possible planting date in the PCR calendar.

The planting window described here considers all the dates when the plants are not subject to continuous drought or severe cycle shortenings due to photoperiod. Silva's definition of optimal-yield planting dates, however, also takes into account factors such as temperature and radiation that are more dependent on the specific variety used. It should also be noted that planting dates that optimize yields are not always adopted by farmers, as these dates do not take into account economic and cultural factors such as the availability of labor, credit and machinery. Also, farmers that plan to plant a second crop after soybeans plant as early as possible in the rainy season, thus accepting suboptimal soybean yields in exchange for the profitability of the second crop (Cohn et al., 2016). For large-scale applications, the wider planting windows presented here are likely to better incorporate the actual range of farmers' choices. The fact that all of Silva's recommended dates are inside the possible planting windows defined by the PCR calendar, and furthermore that they all fall close to the beginning of the PCR-defined windows, suggests that the methods presented here are robust and consistent with field experience.

Table 1
Comparison of possible planting windows based on the photoperiod and climatological rain (PCR) calendar with the recommended planting dates found in Silva et al. (2015). Each column represents a two-week period.

Region	Source	Sep		Oct		Nov		Dec		Jan		Feb	
SB	PCR 2012	x	x	x	x	x	x	x	x	x	x	x	x
	Silva et al. (2015)				x	x	x	x					
MG	PCR 2012			x	x	x	x	x	x	x	x	x	
	Silva et al. (2015)				x	x	x						
MT, MS and GO	PCR 2012		x	x	x	x	x	x	x	x	x	x	x
	Silva et al. (2015)			x	x	x	x	x					
MATOPIBA, except northern MA	PCR 2012			x	x	x	x	x	x	x	x	x	x
	Silva et al. (2015)					x	x	x					
Northern MA and northeastern PA (Pará)	PCR 2012							x	x	x	x	x	
	Silva et al. (2015)								x	x	x		

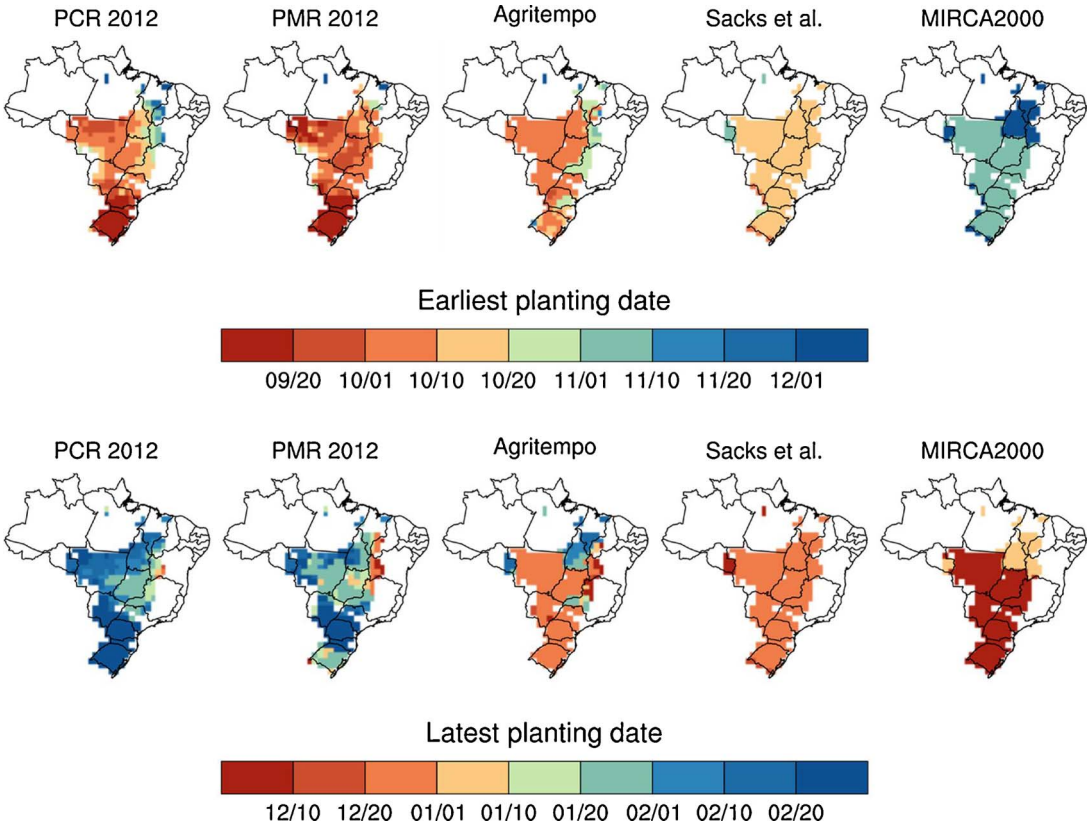

Fig. 8. Earliest and latest planting dates for the PCR and PMR calendars of the year 2012 and for time-invariant datasets used for comparison. MIRCA2000 presents only the start and end of the whole growing season, not defining a specific end for the planting period. Both MIRCA2000's earliest and latest dates presented here are the same and defined as the start of the growing season for their dataset.

A caveat of the methodology used relates to the lack of seasonality of precipitation in southern Brazil. Dry spells are common in that region, but rains are otherwise well distributed throughout the year. For that reason, photoperiod tends to limit planting in SB even though many varieties used today in that region are relatively insensitive to photoperiod. However, the amount of solar radiation, which is correlated with longer photoperiods, is an important factor determining planting dates in that region (Silva et al., 2015). Furthermore, planting in the short-photoperiod months before September also leads to higher chances of frost. Finally, some high-yielding varieties used in southern Brazil are still sensitive to photoperiod (Destro, 2001). For these reasons, our estimates of planting dates in SB are still consistent with the recommendations and datasets used for comparison (see below), even though the actual limiting factor may not be the short photoperiod in some cases.

All three spatial datasets used for comparison also inform planting windows narrower than (and within) PCR2012 (Fig. 8). Sacks et al. (2010) and MIRCA2000, besides including very little real spatial variation within the country, indicate earliest planting 20–30 days and > 60 days after PCR2012 in CB and MT, respectively. Although these dates may be reasonable for single-cropped soybeans, even small delays in planting can decrease the growing-season length below 200 days and render double cropping impossible in a large part of these regions (Fig. 7a). Indeed, earliest planting dates reported by those calendars (Fig. 8, top panel) are later than the PCR2012-estimated latest planting dates for double cropping (Fig. 6h) in several regions, such as GO and parts of MT and MATOPIBA in Sacks et al. and practically all regions except for SB in MIRCA2000 (Fig. 9). This indicates that planting on the dates indicated by those two calendars would not allow for double cropping in those regions, because they would not allow enough time within the rainy season for a second crop. In 2012, 15.9 Mha of soybeans and 5.6 Mha of second-crop maize were planted outside SB. Assuming all the second-crop maize was planted after soybeans (the most common practice), about 35% of soybeans were planted early that year for double cropping, and thus may be misrepresented by MIRCA2000.

On the other hand, the earliest dates in the Agritempo calendar do allow for double cropping (Fig. 9). This was an expected result, as farmers must comply with Agritempo dates to have access to credit at some banks. However, there are self- and trader-funded farmers in double-cropping intensive regions in MT that in many years choose to sow before the safer dates recommended by Agritempo to gain more time for mechanized planting and harvest operations. PCR dates also allow for these cases, showing planting up to 15 days earlier than Agritempo in some regions of central and northern MT (Fig. 8). This difference could have important effects for double cropping in some regions (Fig. 7, Pires et al., 2016).

Still, PCR2012 also represents risk-minimizing dates by considering the climatologically determined dates for rainy season onset in 80% of the years in the dataset. As mentioned, double-cropping farmers tend to start planting as soon as the rainy season starts. The photoperiod and meteorological rain calendar (PMR) accounts for interannual variations of the rainy season, which leads to planting-window start dates more than a month earlier or later than PCR during at least one year across much of Brazil, with the notable exception of RS (Rio Grande do Sul) (Fig. 10). This means that, in 20% of the years, planting on the earliest dates indicated in the climatological PCR calendar would lead to planting too soon, before the rainy season actually started, and thus potentially leading to water stress or no germination. On the other hand, in 80% of the years, the PCR earliest date is after the actual onset, and farmers may have already planted by then. Thus, PMR may be more suitable than PCR for applications such as crop modeling that aim to study double-cropping soybeans, as it captures the temporal variations in both photoperiod and rain. Also, short-term PMR future estimates

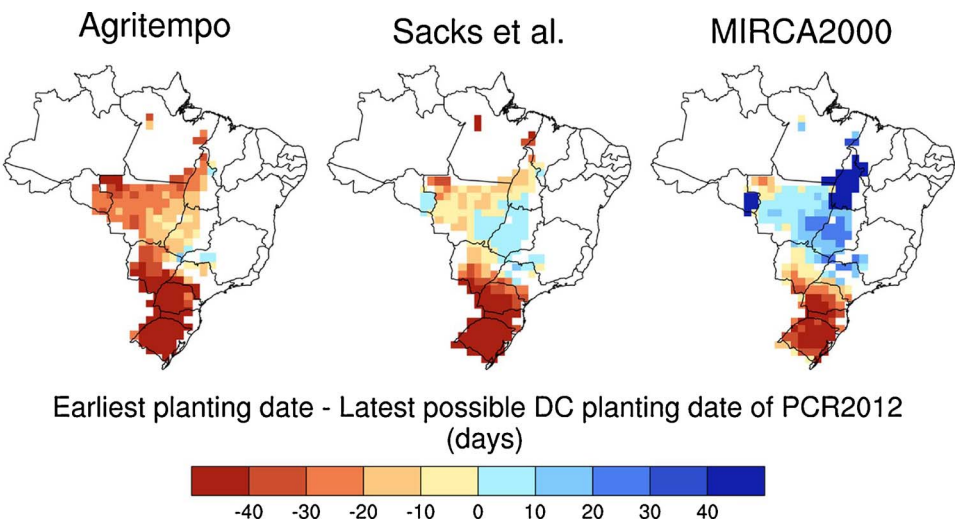
Agritempo
Sacks et al.
MIRCA2000
Earliest planting date - Latest possible DC planting date of PCR2012 (days)
-40 -30 -20 -10 0 10 20 30 40

Fig. 9. Difference between the earliest planting date for each dataset and the latest possible planting date for double cropping from PCR2012. Positive values indicate regions where earliest planting dates reported for each dataset are not suitable for double cropping (DC).

based on weather forecasting could be useful to inform planting decisions.

4. Conclusions

This work documents how soy planting dates have changed since the 1970s, in response to technological changes in photoperiodism of the soy plant, and how these changes allowed the widespread adoption of intensive double-cropping agricultural systems in Brazil. These results are supported by a detailed, year-to-year dataset of soy planting windows for both single and double cropping. This dataset may be used to address questions on the soybean growing season in Brazil, especially those regarding double cropping, and can serve as input for crop modeling studies. The complete dataset is available for download at http://www.biosfera.dea.ufv.br and is shown in Supplementary Figs. S3–S6.

Although the relaxation of photoperiod dependence allowed the rise of soy double-cropping systems in tropical Brazil, analysis of future climate scenarios suggests a possible reduction of areas where rainfed double cropping will be feasible with low climate risk in these same regions. The relaxation made possible the practice of double cropping in most of the state of Mato Grosso and central Brazil, where second-crop maize alone represents 3% of the world's maize production; but changes in the precipitation regime by mid-century are predicted to reduce the area where double cropping is possible in these regions by 17.6% and 16.6%, respectively, assuming conservative management practices. In MATOPIBA, where the soybean crop is rapidly expanding, the reduction is much stronger (61%). This is a consequence of the predicted shortening of the rainy season, which is likely caused by rising CO_2 and deforestation (Pires et al., 2016). The development of (currently hypothetical) shorter-cycle varieties could significantly offset the shortening of the rainy season, leading to smaller reductions in MT (4%) and central Brazil (7%). This would be a less effective solution for MATOPIBA, where 29% of the area where double cropping is currently possible will no longer be so, even with the introduction of these hypothetical varieties. Irrigation is likely to play a role in offsetting these impacts, and it is being increasingly adopted in MATOPIBA. However, logistical and water resources limitations (ANA, 2017) make it unlikely to be a solution everywhere.

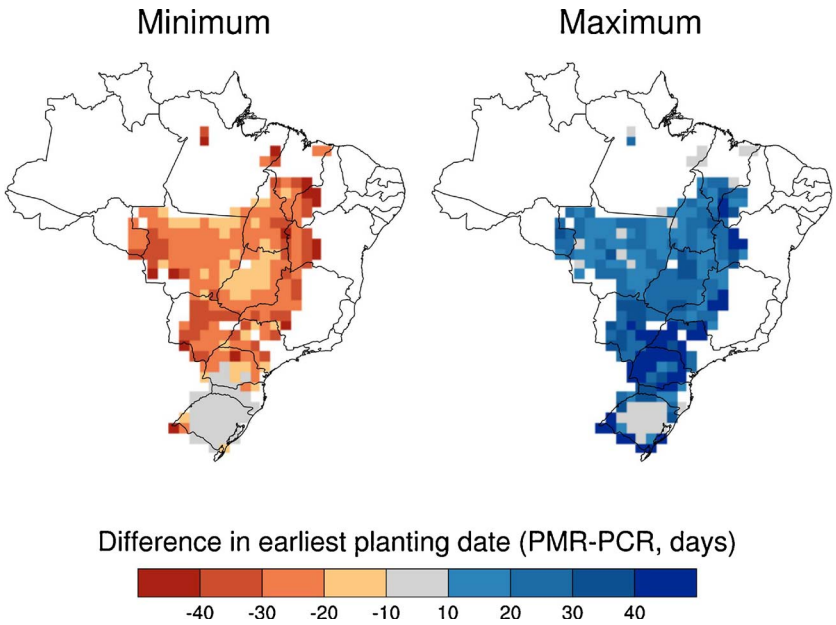

Fig. 10. Minimum and maximum differences between PMR and PCR earliest planting dates across years. Positive values mean the earliest planting date indicated in PMR was later than that indicated in PCR. Differences are due to interannual variation of the rainy season. From the PCR calendar definition, 80% of the years have a negative value, while 20% have a positive value.

Acknowledgements

This research was supported by The Gordon and Betty Moore Foundation, grant 3501. Gabriel Abrahão received additional support from CNPq, process 134516/2014-1.

Appendix A. Soybean harvested area dataset

Soybean harvested area data were obtained from the Brazilian Institute of Geography and Statistics (IBGE) and the Institute for Applied Economic Research (IPEA). The data for 1973–1990 were obtained from IPEA at the municipality level. As many municipalities have changed boundaries in this period, data were aggregated using the Minimum Comparable Areas (MCAs) dataset from Leite et al. (2011, 2012), which consists of the smallest set of municipalities with stable boundaries in the period 1973–1995. For the 1990–2012 period, data were obtained from IBGE for each micro-region, whose boundaries are stable from 1990 forward and are generally smaller than the MCAs considered earlier.

Disaggregation using the GFC (Global Forest Change) dataset was then performed to obtain an estimate of the planted-area distribution at a scale smaller than the administrative unit. For efficiency in processing, the original 30 × 30 m data were resampled to a 1 × 1 km grid, and the inverse of tree-cover data was calculated to obtain nonforest fraction maps. Assuming that soybean harvested area is equally distributed inside the administrative unit's nonforest area, harvested area (A, km^2) for each gridcell i,j was obtained as follows:

$$A_{t,i,j} = NF_{t,i,j}\frac{A_{t,k}}{\sum_{(i,j)\in k} NF_{t,i,j}} \quad (A1)$$

where NF is the nonforest fraction, k is an index representative of each administrative unit and t is the year. For years before 2000, the first year of the GFC dataset, the deforestation map for 2000 was used, thus assuming that distribution of nonforest fractions inside each administrative unit was constant. These assumptions lead to the allocation of harvested area to every pixel with some nonforested fraction, excluding only fully forested pixels. This limitation is partially overcome by using thresholds to exclude very low area values for specific analyses that can be sensitive to them. However, as both assumptions affect only the distribution inside the administrative regions' boundaries, violations do not affect total area values of each region.

Appendix B. Astronomical equations

The derivation of the astronomical equations used here can be found in many textbooks, such as Vianello and Alves (2012). The austral summer solstice photoperiod (N, hours) of the northernmost latitude harvested with soybeans (ϕ) of each year was determined using Eq. (B1), setting the Sun declination angle (δ) to the austral summer solstice value (-23.45°). All angles are represented here in degrees.

$$N = \frac{2}{15^\circ}\arccos(-\tan\phi\tan\delta) \quad (B1)$$

To find the two days in the year that this same N value happens in all other latitudes, first Eq. (B1) is solved for the declination angle (δ):

$$\delta = \arctan\left[-\frac{\cos\left(15^\circ\frac{N}{2}\right)}{\tan\phi}\right] \quad (B2)$$

Then, the solution is used to find the two corresponding days of the year (n_j, one before and one after the solstice) by solving Cooper's equation for n_j:

$$n_j = \frac{365}{360^\circ}\arcsin\left(\frac{\delta}{23.45^\circ}\right) - 284 \quad (B3)$$

The middle of the 45-day vegetative period, the photoperiod-limited planting window, is then obtained by subtracting 23 days from each n_j.

Appendix C. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agrformet.2018.02.031.

References

Alliprandini, L.F., Abatti, C., Bertagnolli, P.F., Cavassim, J.E., Gabe, H.L., Kurek, A., Matsumoto, M.N., de Oliveira, M.A.R., Pitol, C., Prado, L.C., Steckling, C., 2009. Understanding soybean maturity groups in Brazil: environment, cultivar classification, and stability. Crop Sci. 49, 801. http://dx.doi.org/10.2135/cropsci2008.07.0390.

Almeida, L.A.De, Afonso, R., Kiihl, D.S., Albino, M., Miranda, C.De, Jesus, G., Campelo, D.A., 1999. Melhoramento da soja para regiões de baixas latitu des. In: Queiróz, M.A. de, Goe dert, C.O., Ramos, S.R.R. (Eds.), Recursos Genéticos e Melhoramento de Plantas Para o Nor deste Brasileiro. Embrapa Semi-Árido, Petrolina - PE p. 15.

ANA, Agência Nacional de Águas, 2017. Atlas Irrigação: Uso da Água na Agricultura Irrigada. ANA, Brasília – DF.

Arvor, D., Meirelles, M., Dubreuil, V., Bégué, A., Shimabukuro, Y.E., 2012. Analyzing the agricultural transition in Mato Grosso, Brazil, using satellite-derived indices. Appl. Geogr. 32, 702–713. http://dx.doi.org/10.1016/j.apgeog.2011.08.007.

Arvor, D., Dubreuil, V., Ronchail, J., Simões, M., Funatsu, B.M., 2014. Spatial patterns of rainfall regimes related to levels of double cropping agriculture systems in Mato Grosso (Brazil). Int. J. Climatol. 34, 2622–2633. http://dx.doi.org/10.1002/joc.3863.

Bambini, M.D., Junior, A.L., Romani, L.A.S., Otavian, A.F., Koenigkan, L.V., Evangelista, S.R.de M., 2015. Manual on-line do sistema Agritempo versão 2.0. Embrapa Informática Agropecuária, Campinas, SP.

Barretto, A.G.O.P., Berndes, G., Sparovek, G., Wirsenius, S., 2013. Agricultural intensification in Brazil and its effects on land-use patterns: an analysis of the 1975–2006 period. Glob. Change Biol. 19, 1804–1815. http://dx.doi.org/10.1111/gcb.12174.

Bezerra, A.R.G., Sediyama, T., Soares, M.M., 2016. Dessecação pré-colheita. In: Sediyama, T. (Ed.), Produtividade Da Soja. Editora UFV, Viçosa-MG p. 275.

Borchers, A., Truex-powell, E., Nickerson, C., 2014. Multi-cropping practices: recent trends in double cropping. USDA Econ. Inf. Bull. 125.

Boyer, C.N., Stefanini, M., Larson, J.A., Smith, S.A., Mengistu, A., Bellaloui, N., 2015. Profitability and risk analysis of soybean planting Date by maturity group. Agron. J. 107, 2253. http://dx.doi.org/10.2134/agronj15.0148.

Carpentieri-Pípolo, V., Alves de Almeida, L., de Kiihl, R.A.S., 2002. Inheritance of a long juvenile period under short-day conditions in soybean. Genet. Mol. Biol. 25, 463–469. http://dx.doi.org/10.1590/S1415-47572002000400016.

Cavassim, J.E., Filho, J.C.B., Alliprandini, L.F., de Oliveira, R.a., Daros, E., Guerra, E.P., 2013. Stability of soybean genotypes and their classification into relative maturity

groups in Brazil. Am. J. Plant Sci. 4, 2060–2069. http://dx.doi.org/10.4236/ajps.2013.411258.
Cober, E., Curtis, D., Stewart, D., Morrison, M., 2014. Quantifying the effects of photoperiod, temperature and daily irradiance on flowering time of soybean isolines. Plants 3, 476–497. http://dx.doi.org/10.3390/plants3040476.
Cohn, A.S., VanWey, L.K., Spera, S.A., Mustard, J.F., 2016. Cropping frequency and area response to climate variability can exceed yield response. Nat. Clim. Change 6, 601–604. http://dx.doi.org/10.1038/nclimate2934.
CONAB, 2012. Acompanhamento da Safra Brasileira – Grãos 2011/2012 – Décimo Segundo Levantamento. Companhia Nacional de Abastecimento. http://www.conab.gov.br/OlalaCMS/uploads/arquivos/12_09_06_09_18_33_boletim_graos_-_setembro_2012.pdf.
CONAB, 2016. Acompanhamento da Safra Brasileira – Grãos 2015/2016 – Décimo Segundo Levantamento. Companhia Nacional de Abastecimento. http://www.conab.gov.br/OlalaCMS/uploads/arquivos/16_09_09_15_18_32_boletim_12_setembro.pdf.
Correa, P., Schmidt, C., 2014. Public research organizations and agricultural development in Brazil: how did embrapa get it right? Econ. Premise 1–10.
Costa, M.H., Pires, G.F., 2010. Effects of Amazon and Central Brazil deforestation scenarios on the duration of the dry season in the arc of deforestation. Int. J. Climatol. 30, 1970–1979. http://dx.doi.org/10.1002/joc.2048.
Destro, D., 2001. Photoperiodism and genetic control of the long juvenile period in soybean: a review. Crop Breed. Appl. Biotechnol. 1, 72–92.
Dias, L.C.P., Pimenta, F.M., Santos, A.B., Costa, M.H., Ladle, R.J., 2016. Patterns of land use, extensification, and intensification of Brazilian agriculture. Glob. Change Biol. 22, 2887–2903. http://dx.doi.org/10.1111/gcb.13314.
Dirmeyer, Pa., Shukla, J., 1994. Albedo as a modulator of climate response to tropical deforestation. J. Geophys. Res. 99, 20863. http://dx.doi.org/10.1029/94JD01311.
Flaskerud, G., Johnson, D., 2000. Seasonal Price Patterns for Crops. State University Extension Service, North Dakota.
Fuss, S., Canadell, J.G., Peters, G.P., Tavoni, M., Andrew, R.M., Ciais, P., Jackson, R.B., Jones, C.D., Kraxner, F., Nakicenovic, N., Le Quere, C., Raupach, M.R., Sharifi, A., Smith, P., Yamagata, Y., Le Quéré, C., Raupach, M.R., Sharifi, A., Smith, P., Yamagata, Y., 2014. Betting on negative emissions. Nat. Clim. Change 4, 850–853. http://dx.doi.org/10.1038/nclimate2392.
Garcia, R.A., Goulart, A.C.P., Ávila, C.J., Concenço, G., Salton, J.C., 2015. Sucessão soja/soja safrinha em Mato Grosso do Sul: um modelo de produção com sustentação agronômica? Comunicado Técnico 206. Embrapa Agropecuária Oeste, Dourados, MS.
Gavioli, E.A., 2013. Explanations for the rise of soybean in Brazil. In: Board, J. (Ed.), A Comprehensive Survey of International Soybean Research - Genetics, Physiology, Agronomy and Nitrogen Relationships. InTech, pp. 1–26. http://dx.doi.org/10.5772/45867.
Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O., Townshend, J.R.G., 2013. High-resolution global maps of 21st-century forest cover change. Science 342, 850–853. http://dx.doi.org/10.1126/science.1244693.
Hu, M., Wiatrak, P., 2012. Effect of planting date on soybean growth, yield, and grain quality: review. Agron. J. 104, 785–790. http://dx.doi.org/10.2134/agronj2011.0382.
Jones, J.W., Antle, J.M., Basso, B., Boote, K.J., Conant, R.T., Foster, I., Godfray, H.C.J., Herrero, M., Howitt, R.E., Janssen, S., Keating, B.A., Munoz-Carpena, R., Porter, C.H., Rosenzweig, C., Wheeler, T.R., 2016. Brief history of agricultural systems modeling. Agric. Syst. http://dx.doi.org/10.1016/j.agsy.2016.05.014.
Junior, C.P., Kawakami, J., Schwarz, K., Umburanas, R.C., Del Conte, M.V., Müller, M.M.L., 2017. Sowing dates and soybean cultivars influence seed yield, oil and protein contents in subtropical environment. J. Agric. Sci. 9, 188. http://dx.doi.org/10.5539/jas.v9n6p188.
Kastens, J.H., Brown, J.C., Coutinho, A.C., Bishop, C.R., Esquerdo, J.C.D.M., 2017. Soy moratorium impacts on soybean and deforestation dynamics in Mato Grosso, Brazil. PLoS One 12, e0176168. http://dx.doi.org/10.1371/journal.pone.0176168.
Khanna, J., Medvigy, D., Fueglistaler, S., Walko, R., 2017. Regional dry-season climate changes due to three decades of Amazonian deforestation. Nat. Clim. Change 7, 200–204. http://dx.doi.org/10.1038/nclimate3226.
Kucharik, C.J., 2006. A multidecadal trend of earlier corn planting in the Central USA. Agron. J. 98, 1544–1550. http://dx.doi.org/10.2134/agronj2006.0156.
Leite, C.C., Costa, M.H., de Lima, C.A., Ribeiro, C.A.A.S., Sediyama, G.C., 2011. Historical reconstruction of land use in the Brazilian Amazon (1940–1995). J. Land Use Sci. 6, 33–52.
Leite, C.C., Soares-Filho, B.S., Hissa, L.B.V., 2012. Historical land use change and associated carbon emissions in Brazil from 1940 to 1995. Glob. Biogeochem. Cycles 26.
Liebmann, B., Camargo, S.J., Seth, A., Marengo, J.A., Carvalho, L.M.V., Allured, D., Fu, R., Vera, C.S., 2007. Onset and end of the rainy season in South America in observations and the ECHAM 4.5 atmospheric general circulation model. J. Clim. 20, 2037–2050. http://dx.doi.org/10.1175/JCLI4122.1.
MAPA, 2007. Instrução Normativa nº2, Ministério da Agricultura Pecuária e Abastecimento. MAPA, Brasil.
Melo, F.H., 1999. O Plano Real e a Agricultura Brasileira: Perspectivas. Rev. Econ. Pol. 19 (76), 146–155.
Miranda, E.E., Magalhães, L.A., Carvalho, C.A., 2014. Nota Técnica 1: Proposta de Delimitação Territorial do MATOPIBA. Campinas, SP. .
Moreira, V.S., Roberti, D.R., Minella, J.P., Gonçalves, L.G.G., Candido, L.A., Fiorin, J.E., Moraes, O.L.L., Timm, A.U., Carlesso, R., Degrazia, G.A., 2015. Seasonality of soil water exchange in the soybean growing season in southern Brazil. Sci. Agric. 72, 103–113. http://dx.doi.org/10.1590/0103-9016-2014-0056.
Oliveira, L.J.C., Costa, M.H., Soares-Filho, B.S., Coe, M.T., 2013. Large-scale expansion of agriculture in Amazonia may be a no-win scenario. Environ. Res. Lett. 8, 24021. http://dx.doi.org/10.1088/1748-9326/8/2/024021.
Pessôa, E.G.S., Bonelli, R., 1997. O papel do estado na pesquisa agrícola no Brasil. Cad. Ciência Tecnol. 14, 9–56.
Pires, G.F., Abrahão, G.M., Brumatti, L.M., Oliveira, L.J.C., Costa, M.H., Liddicoat, S., Kato, E., Ladle, R.J., 2016. Increased climate risk in Brazilian double cropping agriculture systems: implications for land use in Northern Brazil. Agric. For. Meteorol. 228–229, 286–298. http://dx.doi.org/10.1016/j.agrformet.2016.07.005.
Portmann, F.T., Siebert, S., Döll, P., 2010. MIRCA2000—global monthly irrigated and rainfed crop areas around the year 2000: a new high-resolution data set for agricultural and hydrological modeling. Glob. Biogeochem. Cycles 24, 1–24. http://dx.doi.org/10.1029/2008GB003435.
Ray, D.K., Foley, J.A., 2013. Increasing global crop harvest frequency: recent trends and future directions. Environ. Res. Lett. 8, 44041. http://dx.doi.org/10.1088/1748-9326/8/4/044041.
Ray, D.K., Gerber, J.S., Macdonald, G.K., West, P.C., 2015. Climate variation explains a third of global crop yield variability. Nat. Commun. 6, 1–9. http://dx.doi.org/10.1038/ncomms6989.
Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., Rafaj, P., 2011. RCP 8.5-A scenario of comparatively high greenhouse gas emissions. Clim. Change 109, 33–57. http://dx.doi.org/10.1007/s10584-011-0149-y.
Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A.C., Müller, C., Arneth, A., Boote, K.J., Folberth, C., Glotter, M., Khabarov, N., Neumann, K., Piontek, F., Pugh, T., a, M., Schmid, E., Stehfest, E., Yang, H., Jones, J.W., 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc. Natl. Acad. Sci. U. S. A. 111, 3268–3273. http://dx.doi.org/10.1073/pnas.1222463110.
Sacks, W.J., Deryng, D., Foley, J.A., Ramankutty, N., 2010. Crop Planting Dates: An Analysis of Global Patterns. pp. 607–620. http://dx.doi.org/10.1111/j.1466-8238.2010.00551.x.
Santos, M.G.Pdos, Silva, A.Fda, Sediyama, T., Soares, M.M., 2016. Evolução da produção e da produtividade da soja. In: Sediyama, T. (Ed.), Produtividade Da Soja. Editora Mecenas, Londrina-PA p. 19.
Schnepf, R.D., Dohlman, E., Bolling, C., 2001. Agriculture in Brazil and Argentina: Developments and Prospects for Major Field Crops. Economic Research Service/USDA, Washington – DC.
Sheffield, J., Goteti, G., Wood, E.F., 2006. Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling. J. Clim. 19, 3088–3111. http://dx.doi.org/10.1175/JCLI3790.1.
Silva, F.Lda, Soares, M.M., Silva, A.Fda, Sediyama, T., Borém, A., 2015. Época de semeadura e densi dade de plantas. In: Sediyama, T., Silva, F.L., Borém, A. (Eds.), Soja: Do Plantio a Colheita. Editora UFV, Viçosa-MG p. 198.
Soares-filho, B., Rajão, R., Macedo, M., Carneiro, A., Costa, W., Coe, M., Rodrigues, H., Alencar, A., 2014. Cracking Brazil's forest code. Science 344, 363–364. http://dx.doi.org/10.1126/science.124663.
Spangler, K.R., Lynch, A.H., Spera, S.A., 2017. Precipitation drivers of cropping frequency in the Brazilian cerrado: evidence and implications for decision-making. Weather Clim. Soc. 9, 201–213. http://dx.doi.org/10.1175/WCAS-D-16-0024.1.
Spehar, C.R., 1994. Breeding soybeans to the low latitudes of Brazilian cerrados. Pesqui. Agropecuária Bras. 29 (8), 1167–1180.
Spera, S.A., Cohn, A.S., VanWey, L.K., Mustard, J.F., Rudorff, B.F., Risso, J., Adami, M., 2014. Recent cropping frequency, expansion, and abandonment in Mato Grosso, Brazil had selective land characteristics. Environ. Res. Lett. 9, 64010. http://dx.doi.org/10.1088/1748-9326/9/6/064010.
Spera, S.A., Galford, G.L., Coe, M.T., Macedo, M.N., Mustard, J.F., 2016. Land-use change affects water recycling in Brazil's last agricultural frontier. Glob. Change Biol. 22, 3405–3413. http://dx.doi.org/10.1111/gcb.13298.
Stehfest, E., Heistermann, M., Priess, J.A., Ojima, D.S., Alcamo, J., 2007. Simulation of global crop production with the ecosystem model DayCent. Ecol. Model. 209, 203–219. http://dx.doi.org/10.1016/j.ecolmodel.2007.06.028.
Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2012. An overview of CMIP5 and the experiment design. Bull. Am. Meteorol. Soc. 93, 485–498. http://dx.doi.org/10.1175/BAMS-D-11-00094.1.
USDA, 2017. World Agricultural Supply and Demand Estimates. United States Dep. Agric.
VanWey, L.K., Spera, S., de Sa, R., Mahr, D., Mustard, J.F., 2013. Socioeconomic development and agricultural intensification in Mato Grosso. Philos. Trans. R. Soc. Lond. B Biol. Sci. 368http://dx.doi.org/10.1098/rstb.2012.0168. 20120168.
Viana, J.S., Gonçalves, E.P., Silva, A.C., Matos, V.P., 2013. Climatic conditions and production of soybean in northeastern Brazil. A Compr. Surv. Int. Soybean Res. – Genet. Physiol. Agron. Nitrogen Relationships. pp. 377–392.
Vianello, R.L., Alves, A.R., 2012. Meteorologia Básica e Aplicações, 2nd ed. Ed. UFV, Viçosa-MG.
Waha, K., Van Bussel, L.G.J., Müller, C., Bondeau, A., 2012. Climate-driven simulation of global crop sowing dates. Glob. Ecol. Biogeogr. 21, 247–259. http://dx.doi.org/10.1111/j.1466-8238.2011.00678.x.
Wright, J.S., Fu, R., Worden, J., Chakraborty, S., Clinton, N., Reuter, M., Risi, C., Sun, Y., Yin, L., 2017. A Rainforest-Initiated Wet Season Over the Southern Amazon. http://dx.doi.org/10.1073/pnas.1621516114.
Xavier, A.C., King, C.W., Scanlon, B.R., 2016. Daily gridded meteorological variables in Brazil (1980–2013). Int. J. Climatol. 36, 2644–2659. http://dx.doi.org/10.1002/joc.4518.